Tri-Service Power Expo – Norfolk, VA

Power from Plastic:

How Electroactive Polymer "Artificial Muscles" will Improve Portable Power Generation in the 21st Century Military

Presented by

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SRI International

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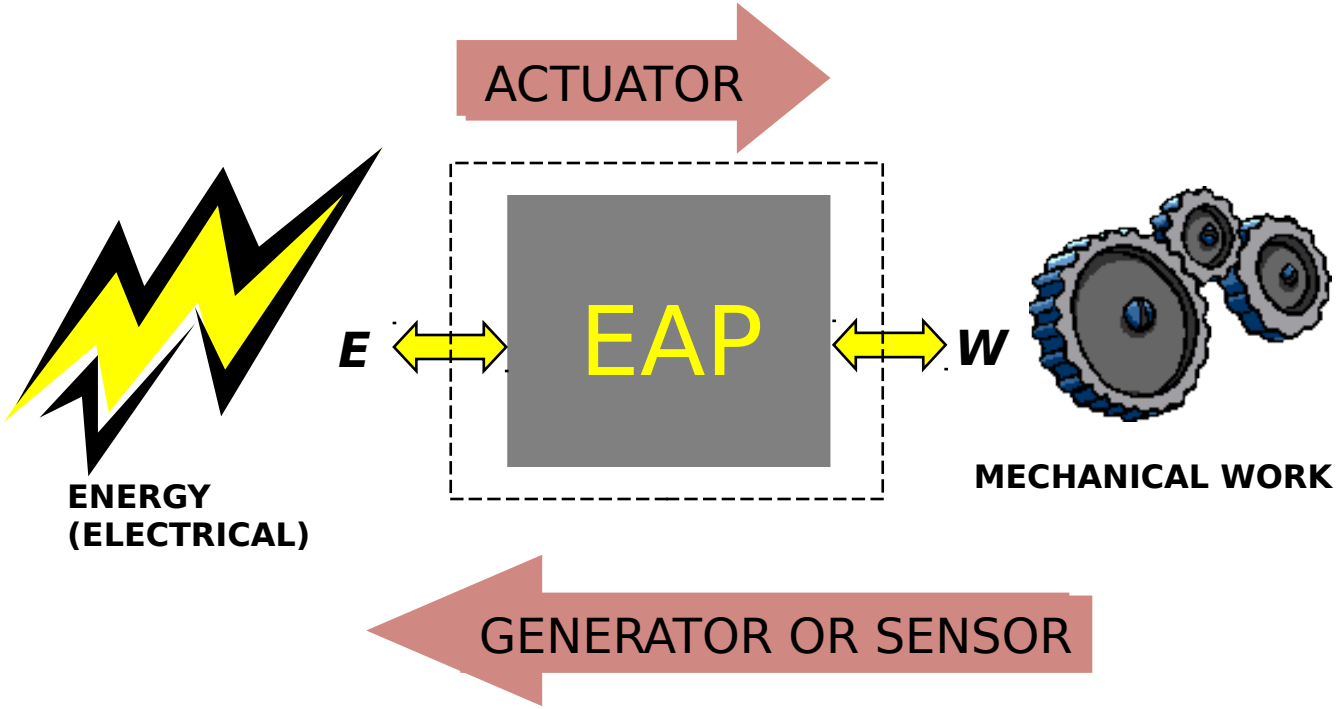
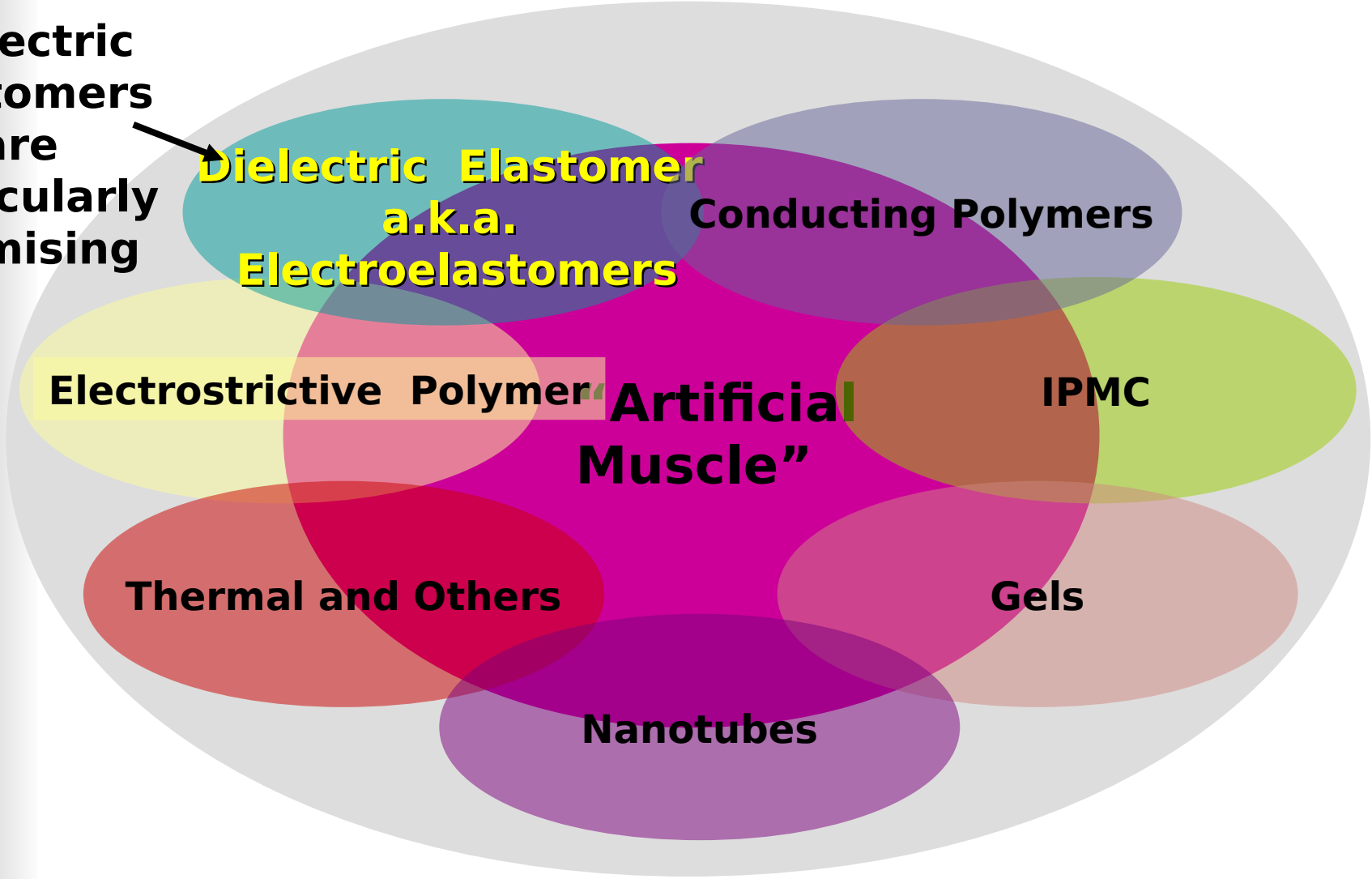
What is an Electroactive Polymer?

- Electroactive polymers (EAPs) convert electrical energy to mechanical work and vice versa



Many Types of EAPs

Dielectric elastomers are particularly promising

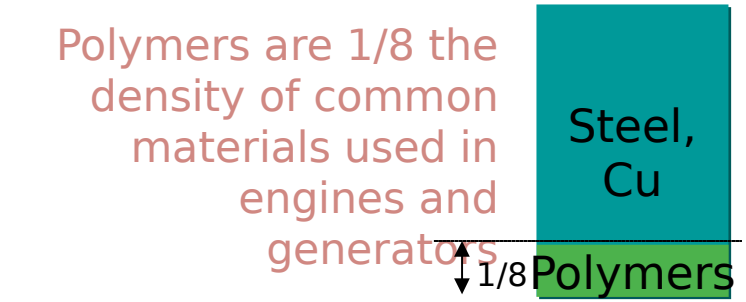


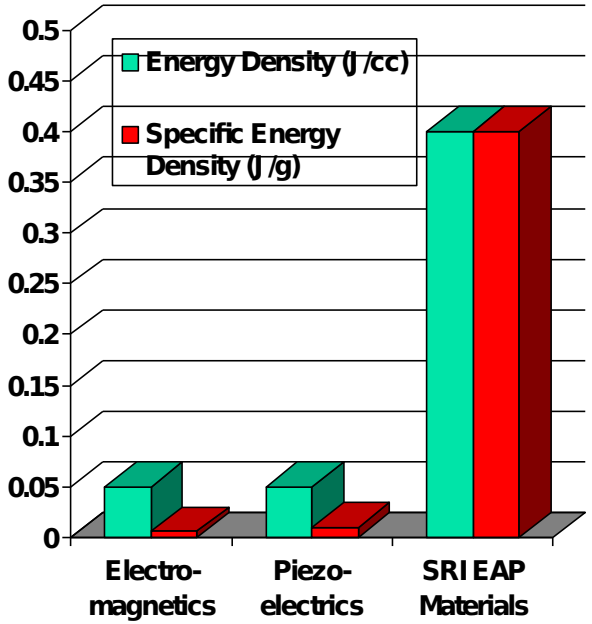
Electroactive Polymer "EAP" Actuators

Advantages of Dielectric Elastomer EAP Power

- **Lighter** – low density, high performance, multifunctional polymers
- **Cheaper** – inexpensive materials, fewer parts, no precision machining
- **Quieter** – high energy density and compliance of polymers allows quiet primarily sub-acoustic operation with few moving parts
- **Softer** – rubbery materials are impedance matched to large motions (e.g. human motion, engines)
- **Versatile** – polymers are scale-invariant; systems can be made in variety of form factors (conformal, elongated, etc.)

Polymers are 1/8 the density of common materials used in engines and generators

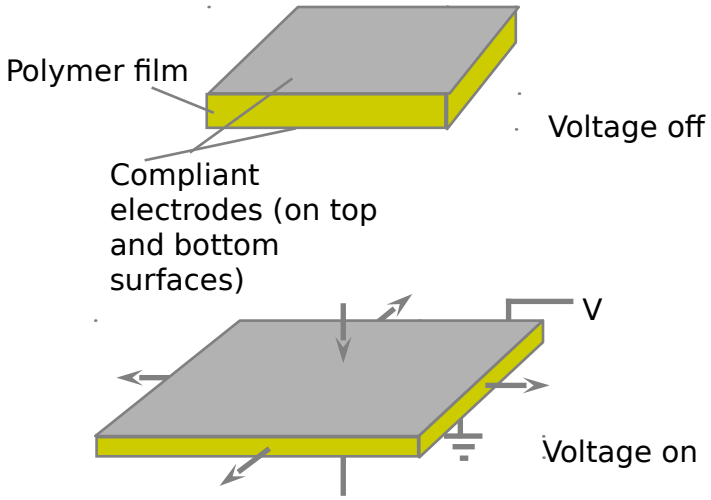




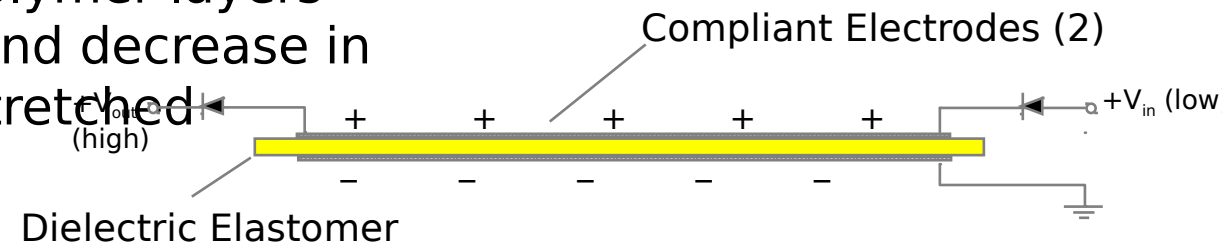
Polymers have more than 10 times higher specific energy density than other transducers

Dielectric Elastomers: Principle of Operation

- Dielectric elastomers are a type of
  EAP that uses an electric field across
  a rubbery dielectric with compliant electrodes
- Variable capacitor generator–energy generated as nearly incompressible polymer layers increase in area and decrease in thickness when stretched



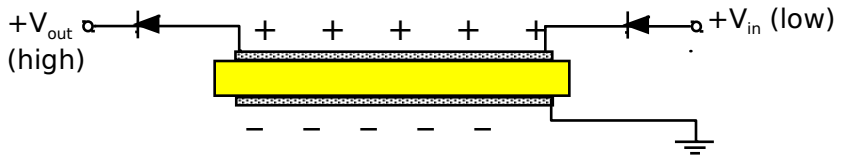
BASIC FUNCTIONAL ELEMENT



EAP STRETCHED

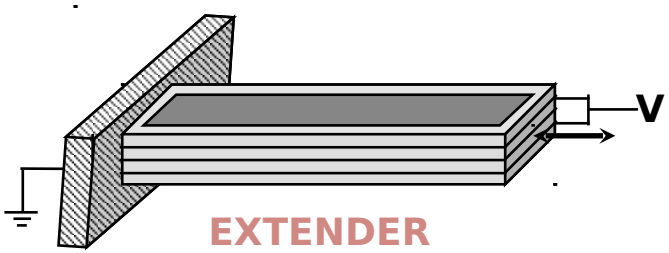
Energy = ½ Q_o^2 ($1/C_f$ - $1/C_i$)

C = ε_r ε_o x film area/film thickness

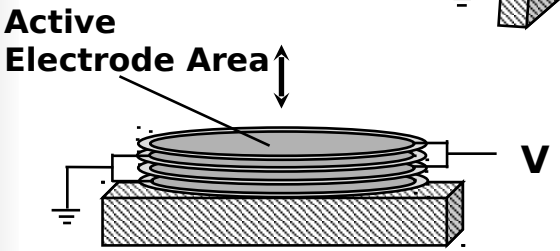


EAP RELAXED

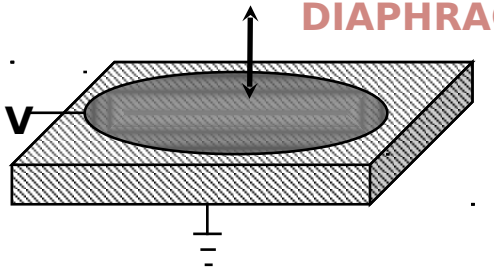
Many Possible EAP Transducer Configurations



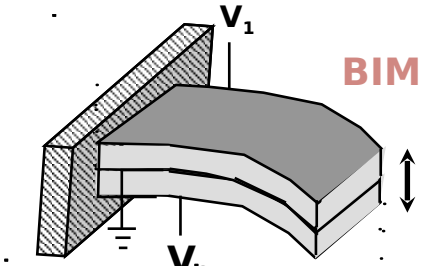
EXTENDER



STACK



DIAPHRAGM



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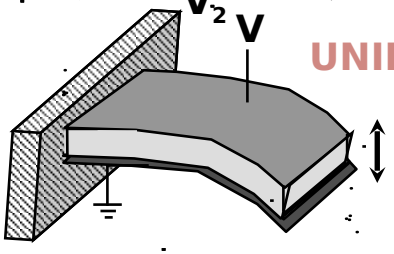
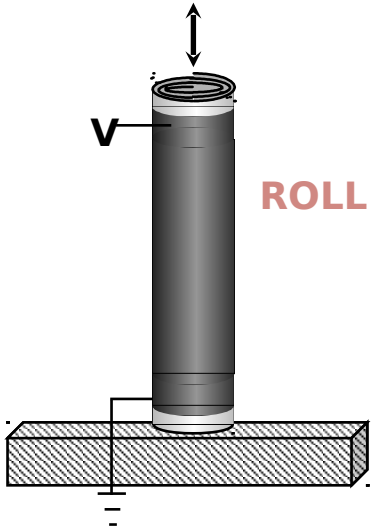
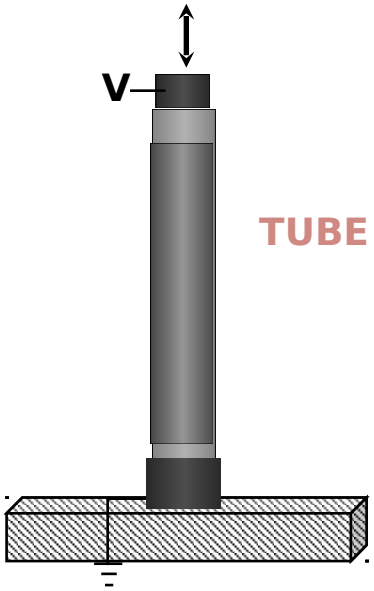


UNIMORPH



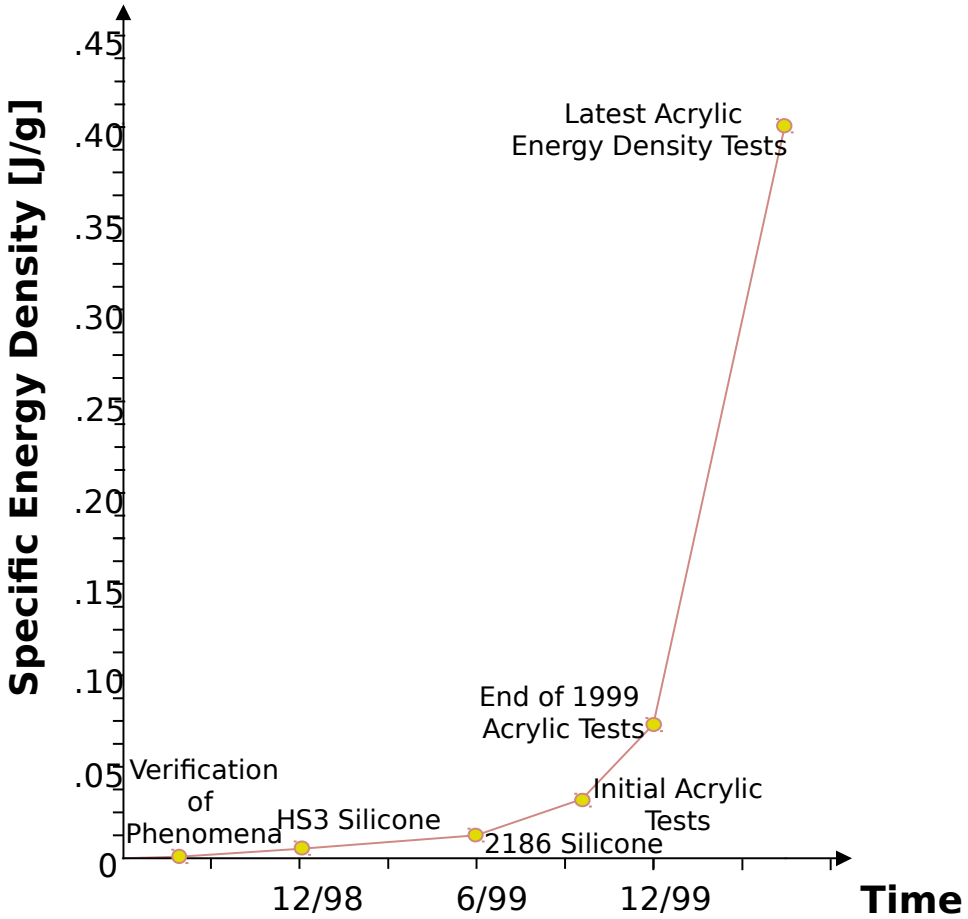
ROLL



TUBE

Polymer Dielectric Elastomer Materials

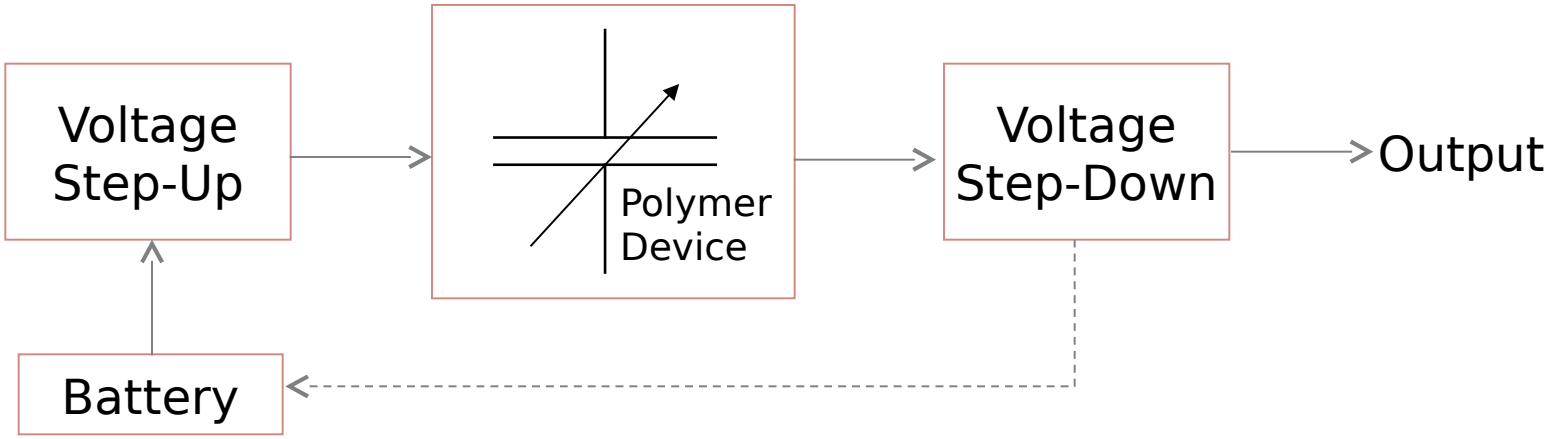
- Several elastomers work well
- Acrylic and silicone are most promising and have shown exceptional energy density
- Acrylic has greater energy density but also greater damping and electrical leakage
- Silicone has exceptional temperature range (–60 to 260 ℃)



Demonstrated Specific Energy Density

Power Conversion and Management

- Power available from dielectric elastomer EAPs is at a high voltage (e.g., 2 kV)
- For most applications we would like to charge batteries at a low voltage (3–48 volts)
- Some applications can use high voltage directly (e.g. night vision optics, in-boot actuators)
- High-voltage is not all bad: low current can allow for thinner, lighter wires and simpler connectors
- Battery or capacitor energy storage is needed to smooth output

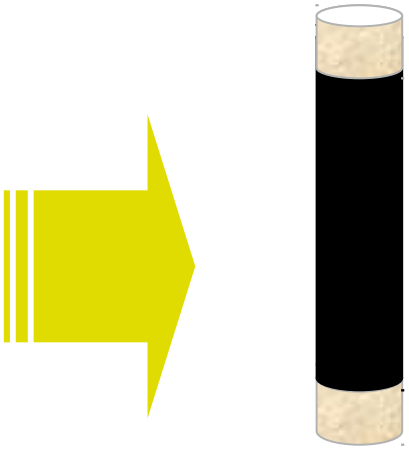


Multifunctionality

- Dielectric elastomers can combine several functions

ACTUATOR or GENERATOR

SENSOR



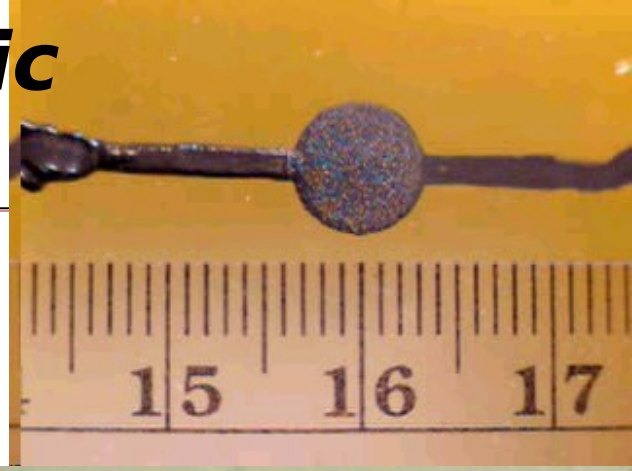
STRUCTURE: Support, Transmission, Spring, Damper

- Simpler
- Lighter
- Higher Performance

Artificial Muscle: Dielectric Elastomer Actuation

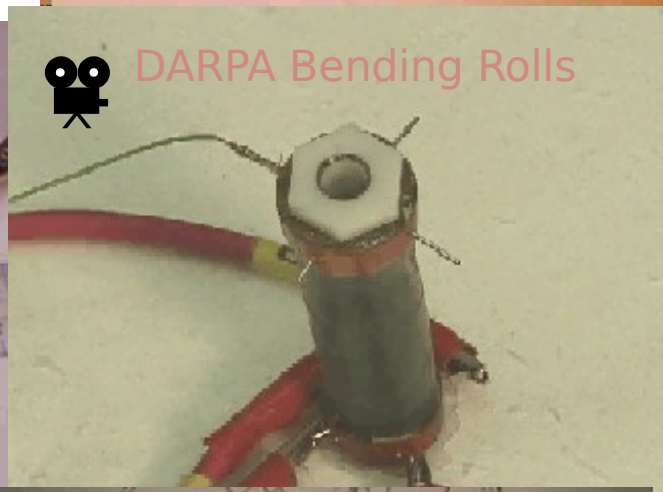
- Dielectric elastomers have already shown unique capabilities in a variety of DoD actuator applications

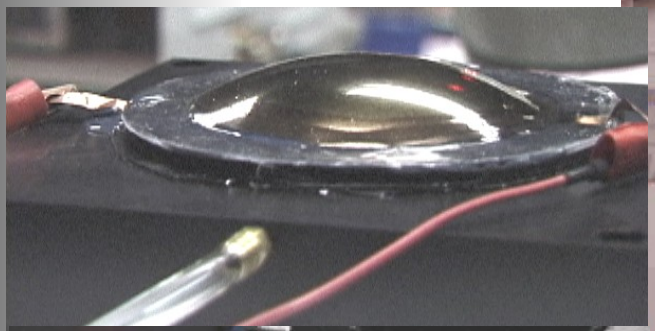
Expanding circle video shows this principle of operation



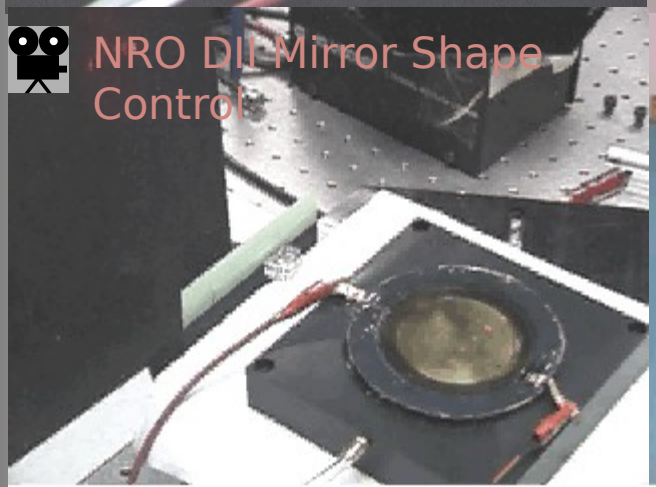
DARPA Artificial Muscle Rolls

DARPA Bending Rolls

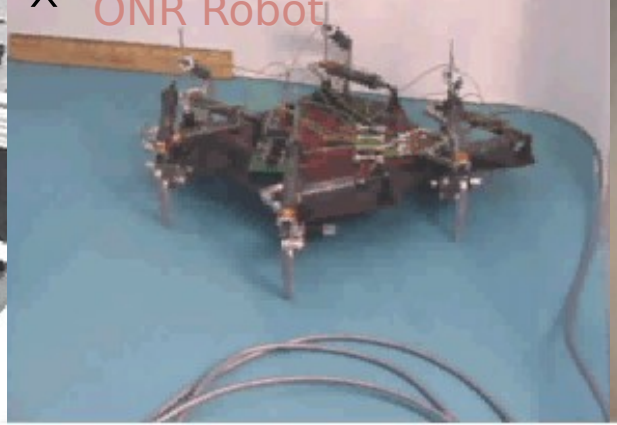


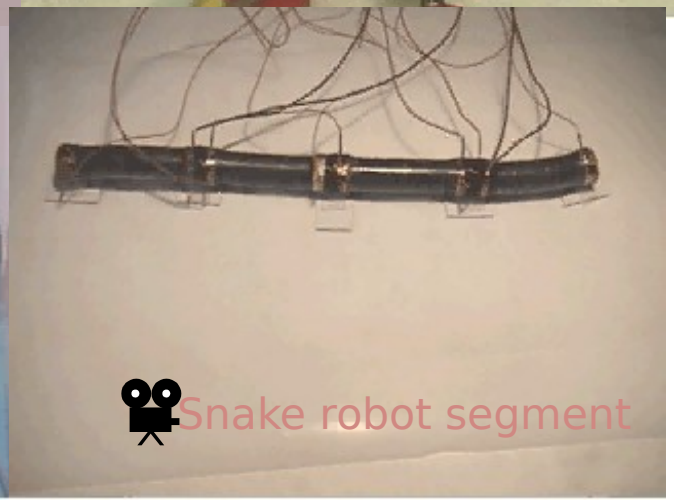


NRO DII Mirror Shape Control



Flex – Insect-Inspired ONR Robot

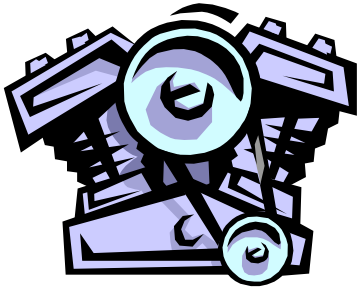




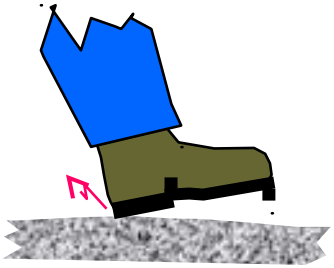
Snake robot segment

Applications that Can Benefit

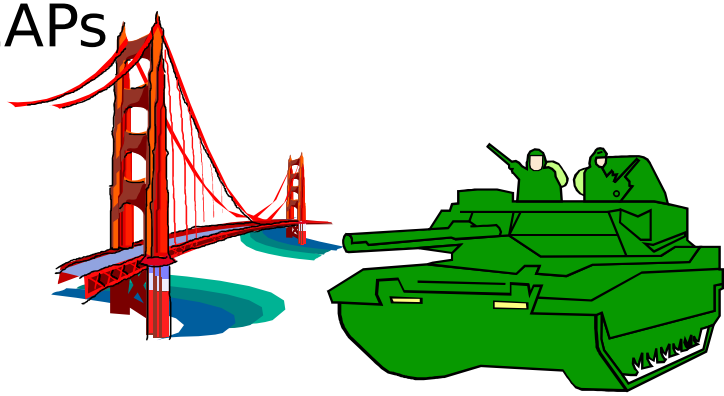
- Many DoD power generation applications can benefit from the advantages of EAPs



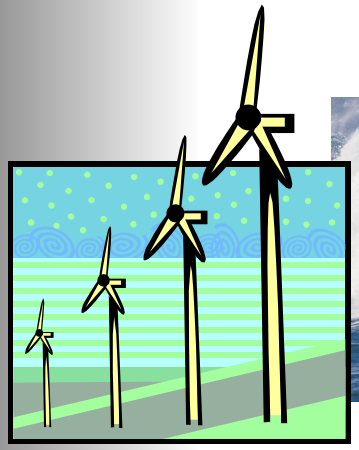
Engine Generators



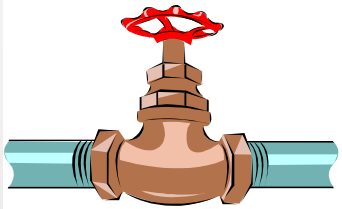
Shoe and other Human-Powered Generators



Parasitic Energy Harvesting



Wave, Wind Power

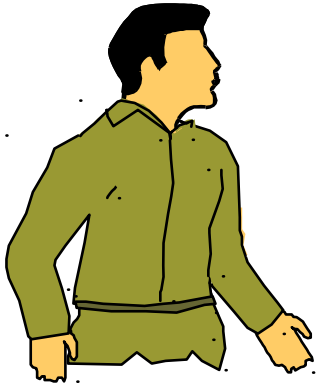


Pumps and valves for fuel management

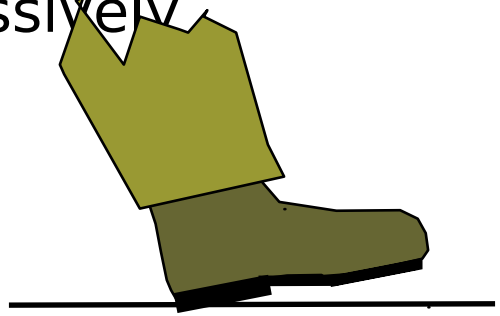
Harvesting Human Movement

- Several possibilities that do not excessively burden the wearer

Backpack Suspension and Padding
0.5–5w

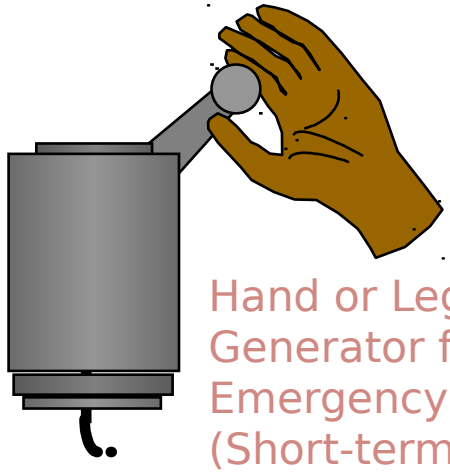


Limb Swing
0.2–3w



Heel Strike and Shoe Flexure
2–20w

Chest or Torso Expansion From Breathing or Routine Movement
0.1–1w

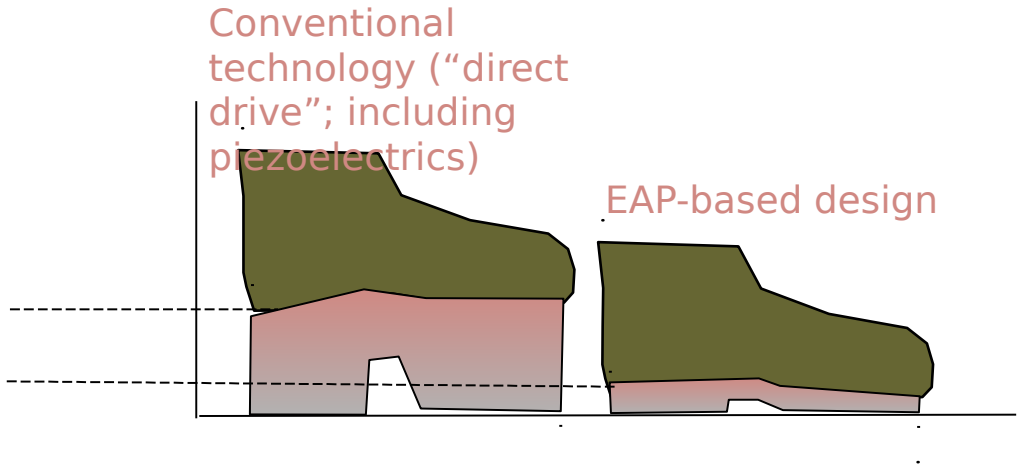


Hand or Leg Cranked Generator for Emergency Back-up (Short-term)
10–100w

Enabling a Heel-strike Generator

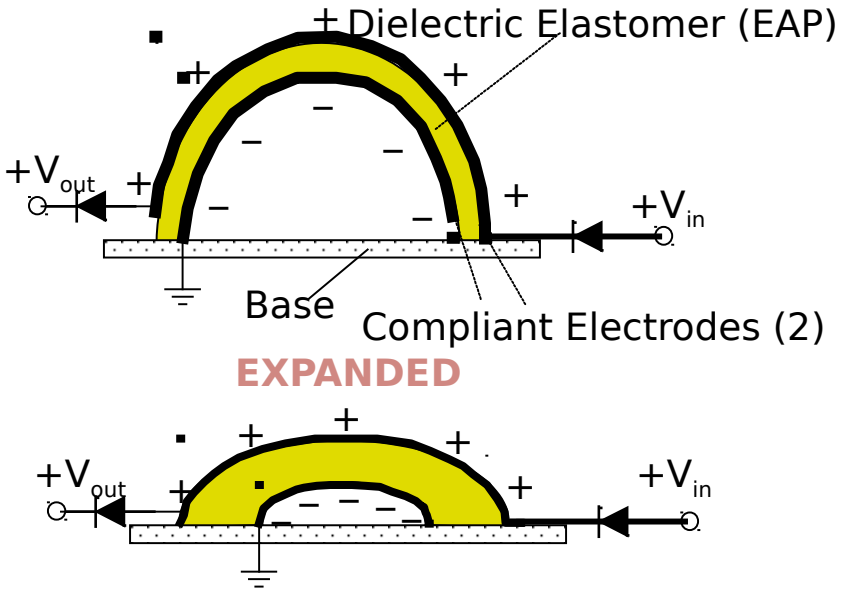
- Energy from the heel strike is “free” - it would otherwise be dissipated as heat
- Energy converted per step with reasonable heel compression can be up to 5 J
- Power generated (both feet) during walking is 1W to 10 W
- The amount of electrostrictive polymers needed to convert 5 J is less than 50 g or 50 cc.
- Electromagnetic or piezoelectric devices would weigh more than 10 times this weight

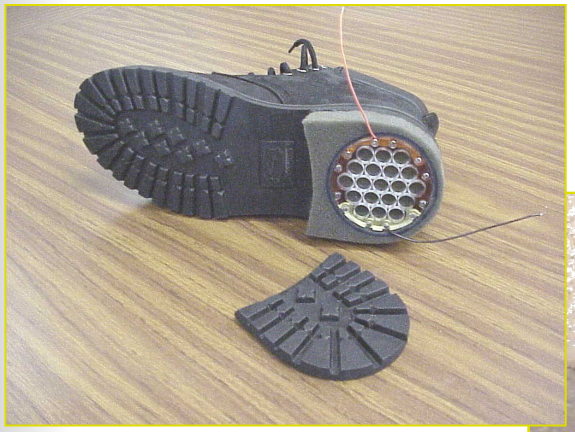
Relative Mass, Size, or Cost for boots with equivalent performance and functionality

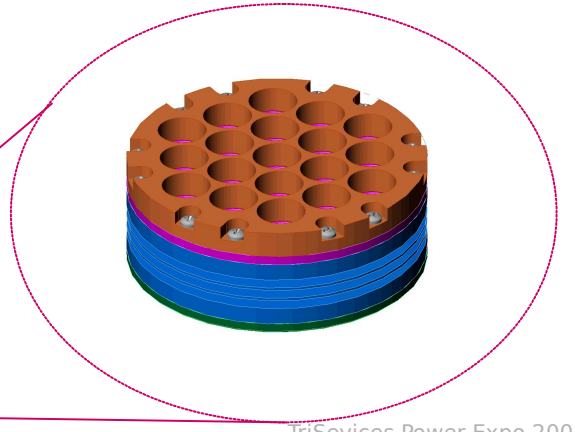


DARPA Heel-strike Generator

- Developed a heel-strike generator to capture free energy while walking
- Demonstrated up to 0.8 J per heel strike
- Developed multi-layer polymer fabrication techniques
  - » Demonstrated 15 layer device







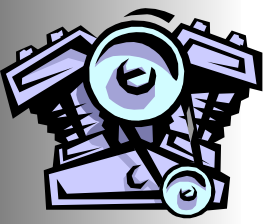
Heel-Strike generators are expected to produce 1W of power under normal walking conditions

Applications of a Heel-strike Generator

OFW Concept
Source: Natick

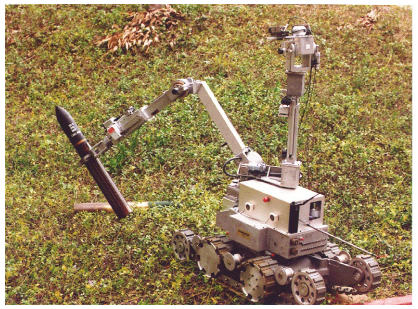
- Boot generator can assist the dismounted soldier in several distinct ways
  - Power source or battery recharger to reduce battery weight for a mission
  - Smart Shoes, Multifunctional Footwear - simplify logistics by reducing the number of separate batteries or devices required
    - power an instrument that should logically be located in a boot for best operation:
      - personal navigation system, medical status monitor, foot warmer
    - power a device that could be located in a boot for weight
      or space savings
      - Friendly ID beacon, comm link, magnetometer, chem/bio detector, special battery or capacitor for high-voltage device such as night vision scope
  - Dynamic Footwear - Actuation or Adaptability for enhanced performance
    - reduced injury
    - improved comfort
    - more efficient load carrying

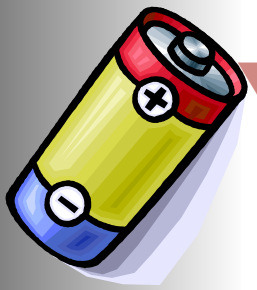
Can EAPs overcome limitations of Small Portable Power Sources?



- Current small fuel-burning engines/generators:
  - Noisy
  - Inefficient (typically 5-7%)
  - Require special fuel mixtures
  - Not inherently hybrids or multifunctional - Need separate components for both mechanical and electrical energy production

MAVs, Land Robots & Vehicles need efficient and quiet Electrical + Mechanical Power

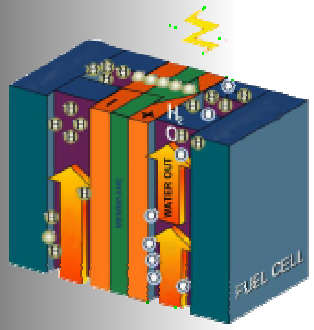




- Batteries:
  - Electric only
  - Low energy density (heavy)
  - Slow to recharge, hard to dispose

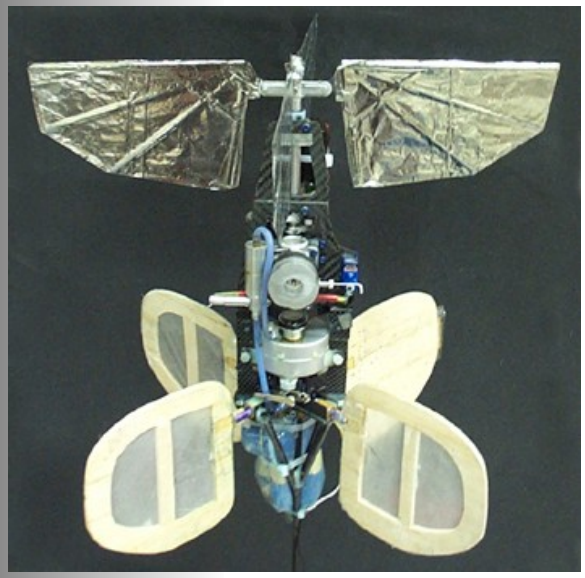
Future Soldier Systems need efficient and quiet Electrical + Mechanical Power

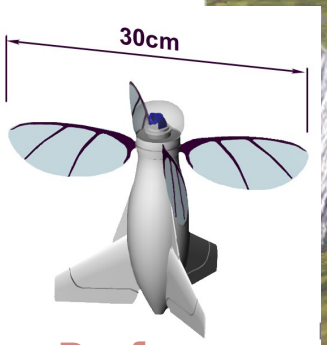
- Fuel cells:
  - Electric only
  - Limited to certain types of fuel and cannot run on dirty fuel
  - Require additional components and warm-up time



Specific Example: Mentor Micro Air Vehicle

- DARPA TTO project for a MAV capable o operation in cluttered environments





Vehicle Specifications:

Total Weight (Wet):	550 g
Engine	140 g
Fuel & Tank	75g
Batteries for electronics and servos	30g

Power required (hover): **98 W**

Performance:

Hover Duration (50g fuel)	8 min.
Payload Capacity:	30 to 70g

Superfly 2.5

"World's First Hovering Ornithopter"

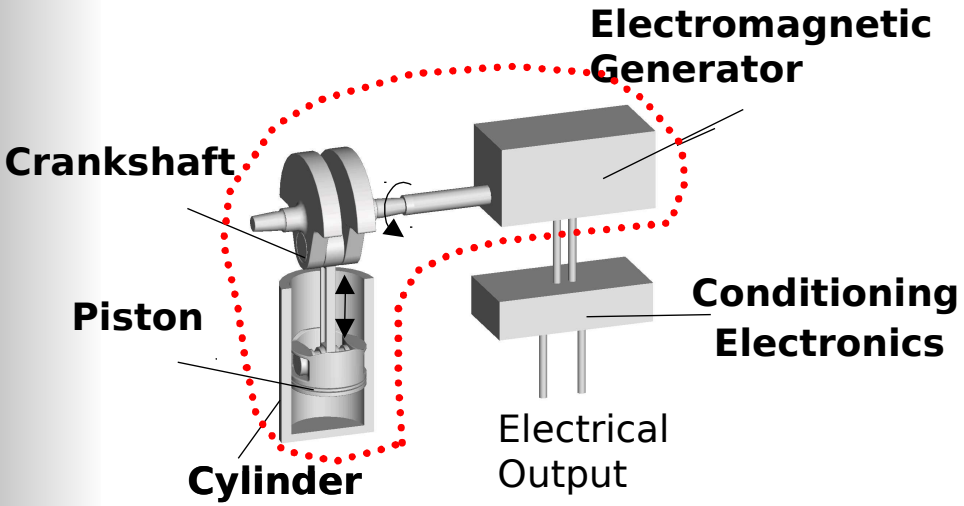
University of Toronto Institute for Aerospace Studies with SRI

DARPA's Palm-Power Program

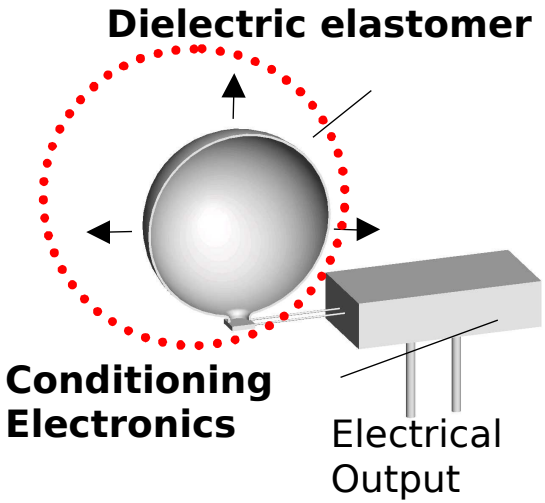
- Specific DoD Needs can be seen in DARPA Palm Power Program Goals:
  - Convert chemical energy of common fuels to mechanical / electrical energy for DoD needs
  - 20 Watt average power level at 12 Volts DC
  - Typical Missions :
    - Three-hour MAV reconnaissance mission - 1000 Whr/kg
    - Three-day Land Warrior mission - 2000 Wh/kg
    - Ten-day special operations reconnaissance mission - 3000 Wh/kg

An All-polymer Engine: The Answer?

- Light: Uses lightweight electroactive polymers instead of metallic piston/cylinders + electromagnetic generator
- Can operate sub-acoustically or with quieter external combustion cycles
- Unlike fuel cells and many small engines, can run efficiently on dirty logistics fuels
- Low cost and rugged – eliminates parts and bearings
- Can be made in a wide variety of shapes and sizes



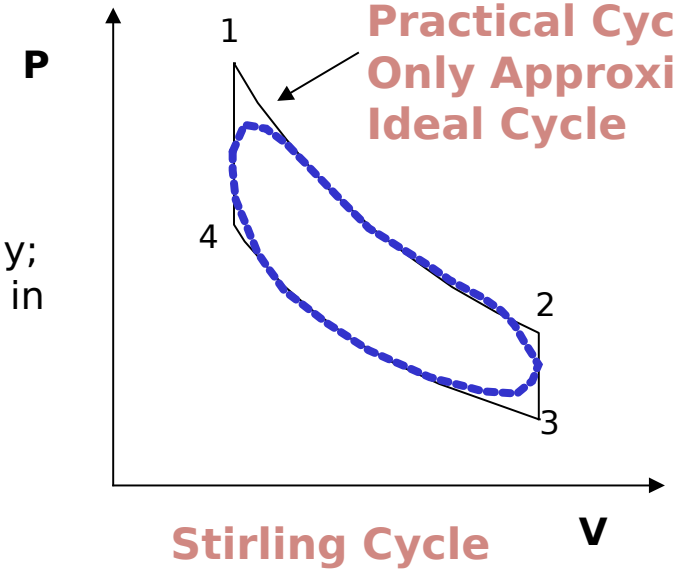
Conventional Generator System



Comparable Polymer Engine System

High Efficiency?

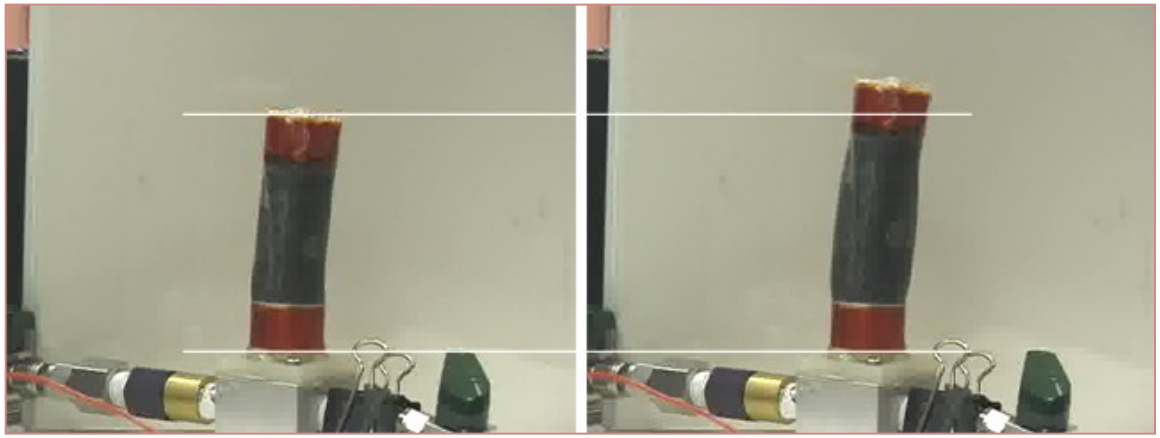
- Polymer engines can potentially be much higher efficiency than IC or other conventional engines:
  - Lower thermal conductivity of polymer walls
  - No sliding surface friction
  - No leakage of expanding fluid
  - Can exploit resonance
  - Opportunity to use novel or optimally tuned thermodynamic cycles
    - Expansion pressure controlled electronically; ability to draw power at virtually any point in cycle
    - Low inertia



20% or more?

Hybrid Power

- Many DoD applications (e.g. robotics, MAVs) require both mechanical and electrical power
- Polymer engine with mechanical and electrical output can eliminates entire transducer steps
  - Fuel cells: chemical → electrical → mechanical
  - IC Engine + generator + motor: chemical → mechanical → electrical → mechanical
  - Polymer engine: chemical → mechanical + electrical
- Hybrid polymer engine saves parts, weight and is more efficient



Combustion inside EAP roll causes linear 23% expansion that could be used for both electrical and mechanical output

By the Numbers

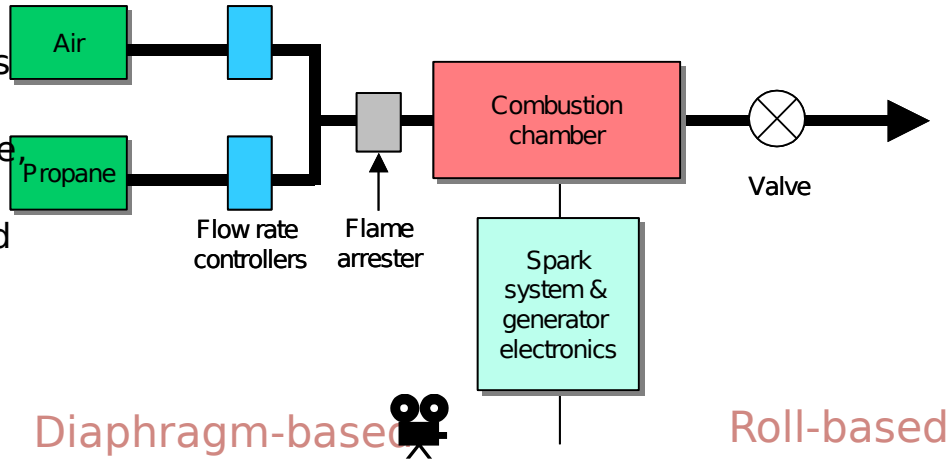
- Polymer engines promise better overall performance than existing electrical and mechanical power sources

Approach	Efficiency (%)	Power density (W/g)	Output	Noisy
IC engine	6	2	Mechanical only	Very
Fuel Cell	30	0.1	Electrical only	No
Electric Motor	20-80	1	Mechanical only	Somewhat
Electrical generator	70-80	1	Electrical only	Somewhat
Polymer engine	20	4	Electrical + Mechanical	No

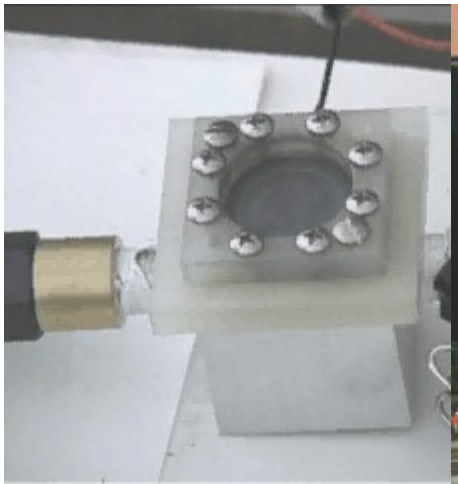
Can it be done?:Polymer Engine First Steps

- Successful demonstration of polymer engines operating with high temperature combustion gases (>1000 ºC) for over 3 hrs at 3 Hz
  - High temperature operation allows for high thermodynamic efficiency
  - Micro-pitting observed, coatings could prevent pitting
  - Energy density already similar to batteries (500 Whr/g)
- Multiple fuels demonstrated (butane, propane, hydrogen)
- External combustion cycle also demonstrated

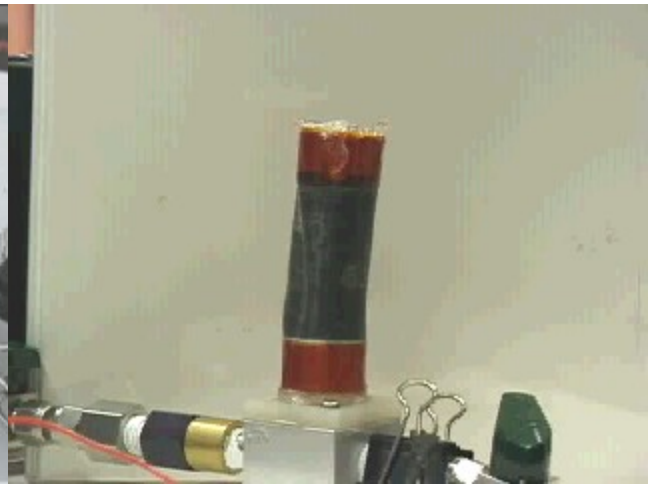
DARPA/ARO program aimed at addressing the key technical challenge – **Can a polymer "cylinder" survive combustion?**



Diaphragm-based

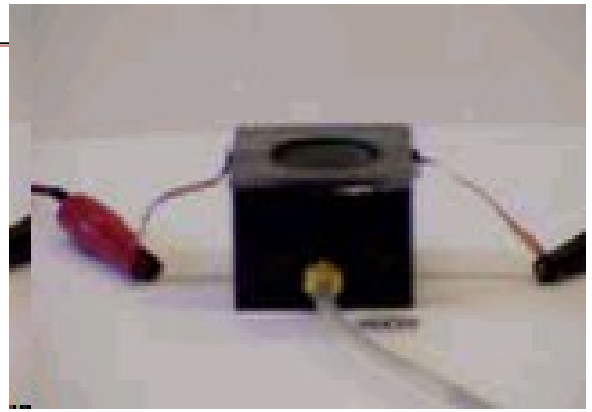


Roll-based



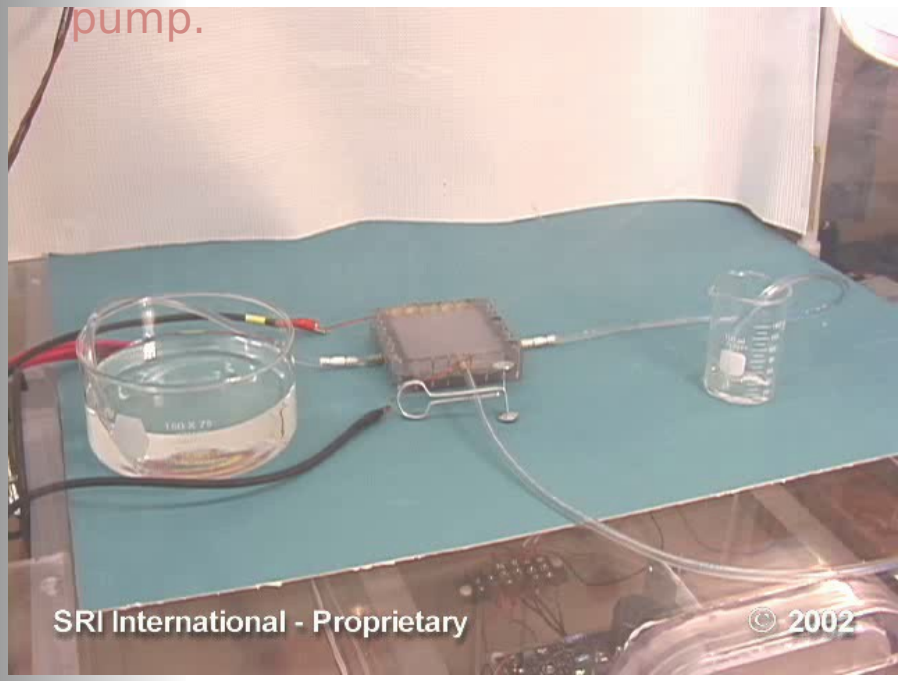
Other Power Applications of EAPs

- Polymer actuators may offer advantages for other power systems
  - Valves & pumps for fuel cells
  - Actuated valves for engines, air controls, fuel pumps, etc.



Polymer diaphragms can provide large displacements for lightweight pumps

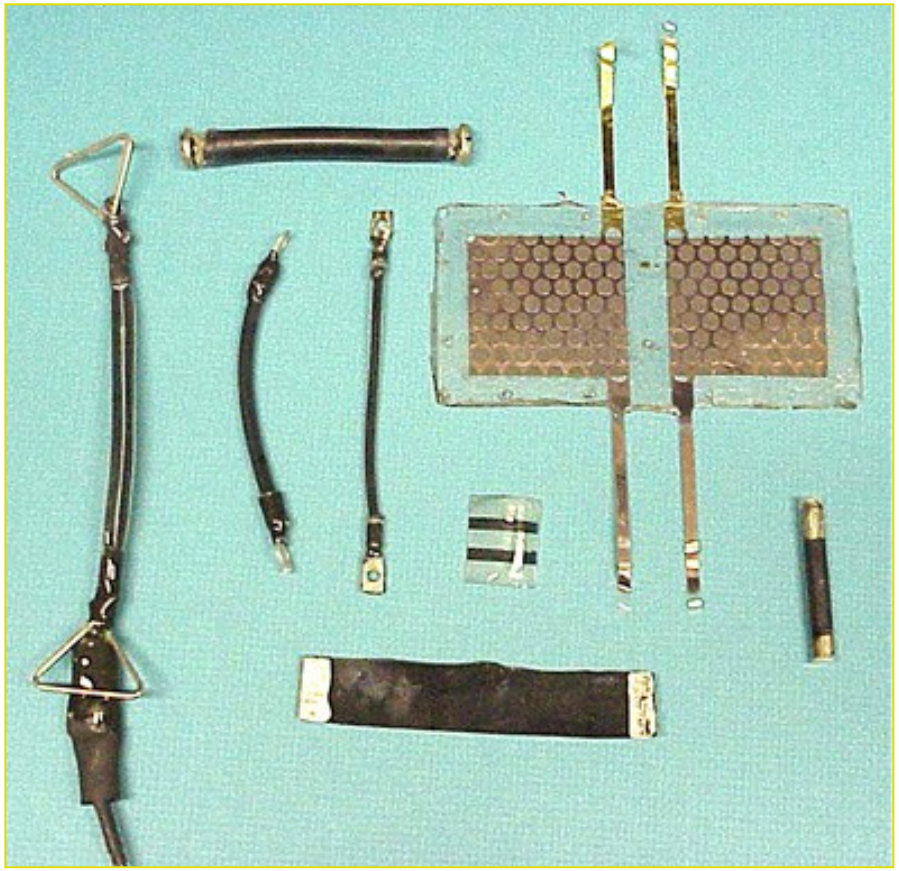
Proof-of-principle diaphragm array pump.



Dielectric elastomer actuator for direct control of engine valving

Simple Sensors

- Simple low-cost large-strain sensor is a simple embodiment of a generator
- Well suited for:
  - Human motion (Plethysmography, Kinesiology)
  - Computer input devices for virtual reality applications etc.
  - General purpose displacement detector for low-cost instrumentation and measurement
  - Low-cost position, force or pressure sensors for actuators, generators, etc.



Large variety of sensors can be based on dielectric elastomers

Power from Plastic?

- EAPs are promising for addressing a variety of DoD power generation challenges
- First proof-of-principle devices made and tested
  - Variety of transducer configurations
  - Heel-strike generator
  - Polymer engine
- Improved devices are under development
  - Lifetime issues are being addressed
  - Electronics for power management is a key challenge

Acknowledgements

- DARPA
- MITI/NEDO
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- NRO
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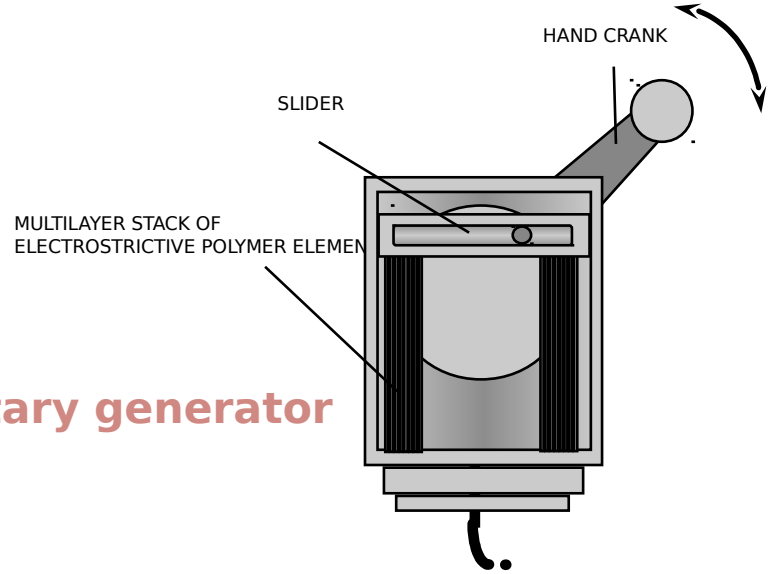
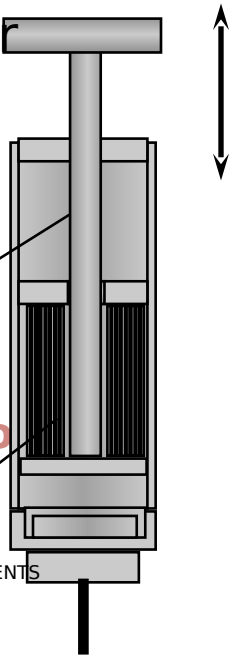
- The numerous SRI employees who have contributed to the work presented here: Ron Pelrine, Qibing Pei, Richard Heydt, Don Czyzyk, Phil Jeuck, Marcus Rosenthal, Scott Stanford, Harsha Prahlad, Neville Bonwit, Seajin Oh, Shari Shepherd, Joe Eckerle, Jon Heim, John Marlow, Surjit Chhokar, Jose Joseph, Dave Flamm, Dave Huestis, Karen Nashold, Jeff Simons, Tom Cooper and more.
- See www.artificialmuscle.com

Human-Powered Generators

- Large-strain capability of electrostrictive polymers allows for simple and efficient integration into generators
  - » efficiency is not speed dependent
  - » device can weigh 10x less than an electromagnetic generator with the same output rating
- Novel generator designs with few moving parts are possible
- Similar devices can also be couple to non-human power sources (e.g. engines, wind turbines)



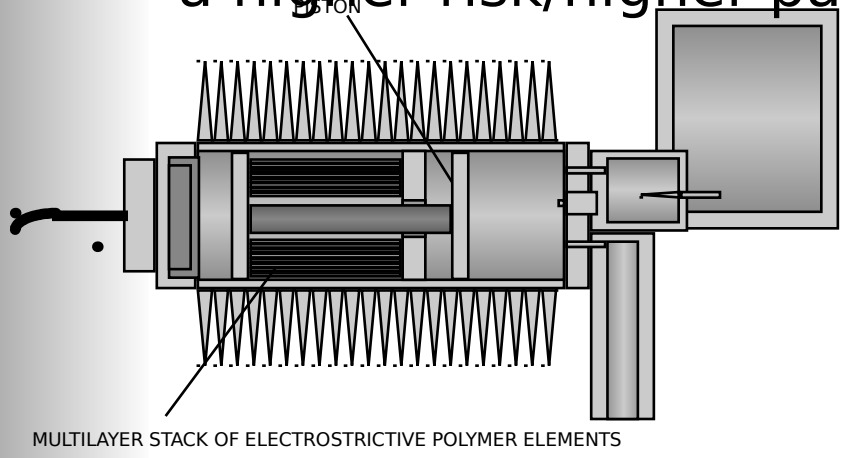
Rotary generator



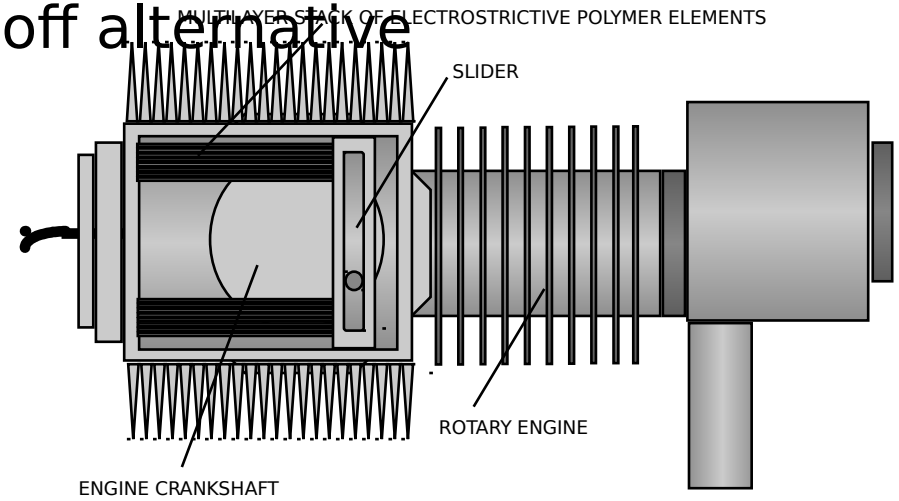
Linear generato

Lighter Generators for Engines

- High energy density and large strain capability of EAPs allows for simple, lightweight and efficient integration with combustion engines
- Novel engine/generator designs are may be a higher risk/higher payoff alternative



Linear generator/piston engine combination



Rotary generator/engine combination